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Laser Cutting of Carbon Fiber Reinforced Polymers using Highly Brilliant Laser Beam Sources

Annett Klotzbach*[1], Markus Hauser[1], Eckhard Beyer[1,2]

[1]*Fraunhofer Institute for Material and Beam Technology, Winterbergstrasse 28, 01277 Dresden, Germany*
[2]*University of Technology at Dresden, Institute of Surface and Manufacturing Technology, Chair for Laser and Surface Technology, George-Bähr-Str. 3c, 01069 Dresden*

Short Abstract

Carbon fiber reinforced polymers (CFRP) are applied more and more in the aircraft industry as well as in the automobile industry. The principal reason is the highly mechanical load capacity along with the low density. Moreover, the corrosion resistance plus the damping behavior of the material can be utilized fully in highly stressed structures. However, the concept of manufacture CFRP-parts close to the final contour does not substitute the need of cutting them. The different properties of fiber- and matrix-material constitute an ambitious challenge while cutting CFRP using a laser beam. This paper deals with elementary analysis of the laser remote cutting process and the gas assisted laser cutting of CFRP.

Keywords: laser; cutting; remote; gas assisted; carbon fiber reinforced polymers; CFRP

1. Motivation

Within the transportation industry, the present trend requests resources-economized designs. In addition to novel engine concepts, a basic principle is reducing the mass of the main parts of the vehicle. Thus, carbon fiber reinforced plastics find their way into structures of automobiles and aircrafts [1]. Comparing those to typical, homogenous lightweight design materials e.g. aluminum and titanium, the main difference is the structure of CFRP. It is an assembly out of fibers and a matrix (Figure 1a). While the fibers ensure an excellent tensile strength and stiffness, the matrix guarantees compressive and bending strength and supports the fibers (Figure 1b, 1c). Using CFRP, the given requirements concerning the stress of a specific part allows adapting the structure of the material. Here, the fiber type (long/short/endless), the fiber orientation and the fiber percentage, as well as the type of the matrix material (duro-/ thermoplastic) affect the final characteristic of the part significantly.

* Corresponding author. Tel.: +49 351833913235.
E-mail address: annett.klotzbach@iws.fraunhofer.de.

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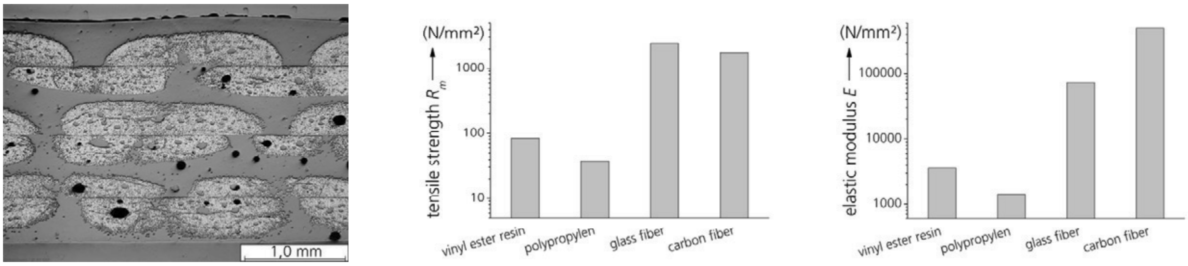


Figure 1: (a) Cross section of CFRP with duroplastic matrix, (b), (c) tensile strength and elastic modulus of typical matrix and fiber materials [2; 3]

The very same benefits of CFRP which are used in lightweight design parts challenges conventional cutting techniques. Whether mechanical processes (milling, drilling), water jet cutting or laser cutting – the main issue is the different characteristic of fiber and matrix. Hence, the following problems accompany the cutting of CFRP and other fiber reinforced polymers [4; 5; 6]:

- Damage of the material surface and the composite → additional process required (sealing)
- Inhomogeneous cutting kerf, depending on the fiber orientation (delamination, flaking, overhanging fibers)
- Emission of dust, gas and waste products

Applying pulsed laser cutting systems to minimize the damage of the cutting edge, the ablation rate reduces dramatically. Moreover, different thermo-optical characteristics of fiber and matrix influence the process. The carbon fibers have a more than ten times higher sublimation temperature than the decomposition temperature of the resign. Because of a good heat conduction of the fibers, the resign fitting at the fibers will be decomposed quickly before the carbon fiber itself is cut. The theory to decrease the heat affected zone is to minimize the interaction time between laser radiation and material.

The benefit of the availability of high power and high brilliant laser sources make ablation and/or cutting processes with high processing speeds possible. However, the relations between wavelength and absorption on nonisotropic material on the one hand and intensity influence and processing speed on the other hand need fundamental research.

2. Experimental

Within the experiments, three laser beam sources were applied – a singlemode fiber-laser, a multimode fiber-laser and a CO_2-slab laser. Furthermore, gas assisted laser cutting (Figure 2a) and remote laser cutting (Figure 2b) were tested. Combining laser source and process principle, five experimental runs were realized, most of them on two different materials.

The wavelength of a laser source and the intensity, hence the laserspot size, play significant roles in terms of comparing fiber- and CO_2-lasers. Due to improved focusing behavior of fiber-lasers based on a ten times shorter wavelength, the obtained intensity is typically much higher than those of CO_2-lasers. Assuring comparability, the experimental runs using multimode fiber laser and CO_2-laser were operated by use of similar intensities. Thus, the absorption of the material with respect to the laser source is placed in the center of the research. Additionally, the singlemode fiber-laser was run with superior intensity to evaluate the effect of increasing the intensity.

Gas assisted laser cutting is running at velocities of some ten m/min (1…20 m/min). In contrast, remote laser cutting realizes spot velocities of some ten m/s (1…20 m/s). This affects the interaction time of the laser beam on the work piece dramatically by the factor of 60. Furthermore, remote laser cutting allows a cyclic ablation until the cutting kerf is formed completely. The effective velocity to compare laser remote cutting to gas assisted laser cutting is calculated by division of laser spot velocity by needed cycles. In first approximation the pauses during the processing were not taken into account.

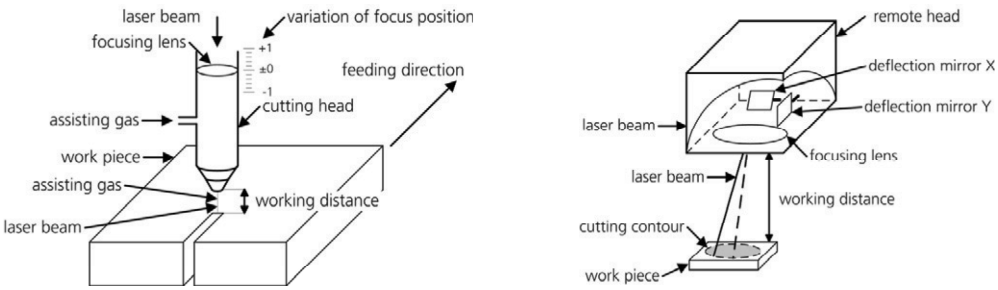


Figure 2: Schematic diagram of (a) gas assisted laser cutting and (b) remote laser cutting

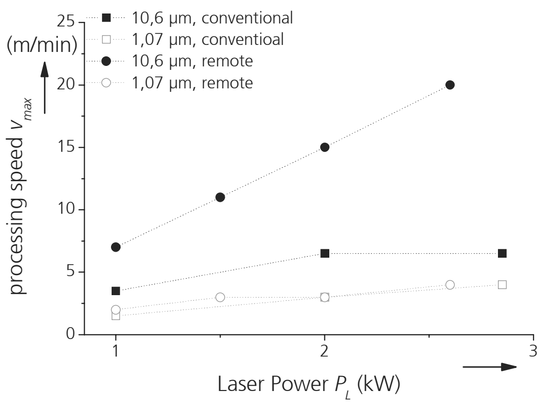
The analyzed material was 2.4 mm thick consolidated CFRP with vinyl ester resin. Its fiber percentage is 50% (in order to the weight). Additionally, the adequate non-consolidated material, a carbon fiber non-crimp fabric, was cut. Its thickness is 0.4 mm. The fiber orientation is ± 45°.

Table 1: Range of parameters for gas assisted (g) and remote (r) laser cutting

parameter	unit	process	gas assisted laser cutting	remote laser cutting
approximately spot diameter	µm	g, r	240	240/ 50
laser power	kW	g, r	1…2.85	1…2.6
focus position	mm	g, r	± 1,0 / ± 2,0	± 1,0 / ± 2,0
nozzle distance	mm	g	1,0…3,0	-
feeding velocity	m/min	g	1…100	-
assisting gas	-	g	N_2, He, air	-
assisting gas pressure	bar	g	1…20	-
laser spot velocity	m/s	r	-	0.25…10
maximum cycles	-	r	-	40
time between cycles	s	r	-	> 1

3. Results and discussion

It could be found that consolidated CFRP and carbon fiber non-crimp fabric can be cut using fiber- and CO_2-laser plus gas assisted and remote laser cutting. The superior cutting velocity for consolidated CFRP machined with CO_2-laser reflects the improved absorption of polymers regarding to CO_2-radiation. Moreover, the remote technology increases the maximum cutting velocity up to 20 m/min for multi-kW laser power (Figure 3a). Here, the material in the cutting kerf has to be vaporized completely. The results of the process efficiency, defined as the energy input per unit length (for a determined material thickness) is documented in Figure 3b. Typical characteristics of remote processing are the short interaction between laser beam and work piece.



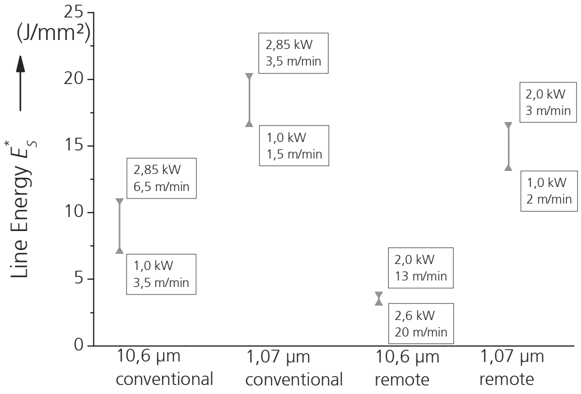


Figure 3a (left): dependence on laser power to processing speed for cutting of CFRP (process trials: convent. cutting with gas assistance; remote cutting, CO_2-/YAG-laser, focus diameter: approx. 240 µm)
Figure 3b (right): efficiency – comparison for different process trials using comparable focus diameters

This results a damage-reduced cutting zone compared to gas assisted laser cutting (Figure 4). Depending on the fiber distribution the matrix displacement is obvious.

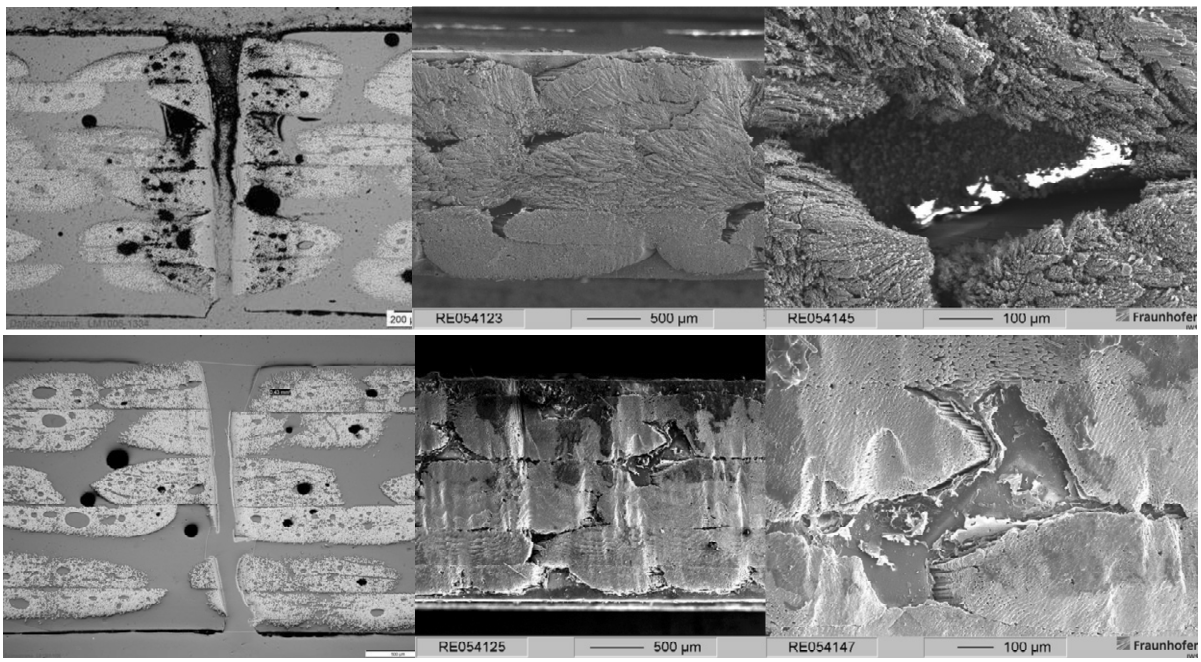


Figure 4.1 – 4.4 (top): images of CFRP cutting area, realized with the following optical configuration:
CO_2 – laser, conventional cutting with gas assistance (from left: cross section, REM – image overview, detail of matrix reduction)

Figure 4.5 – 4.8 (bottom): images of CFRP cutting area, realized with the following optical configuration:
CO_2 – laser, remote cutting (from left: cross section, REM – image overview, detail of matrix reduction)

The images 4.3 and 4.4 of the raster electron beam microscope show the typical surface of a thermal gas assisted cut. A solid graphite layer without single carbon fibers and grooves are to been seen. Differences become visible when comparing this cutting area with one, which has bee processed by remote cutting (Figure 4.5 – 4.8. Some grooves and partly the single fibers are present. The matrix displacement, measured at certain positions is in the range of 100 – 150 µm, compared to conventional cutting with more than 500µm.

Furthermore, increasing the laser spot velocity during the remote-processing narrows the heat affected zone significantly (Figure 5). But of course the numbers of cycles have to be increased. Further research has to be done to find the optimum between spot velocity and ablation rate for the realization of efficient processes with good cut quality.

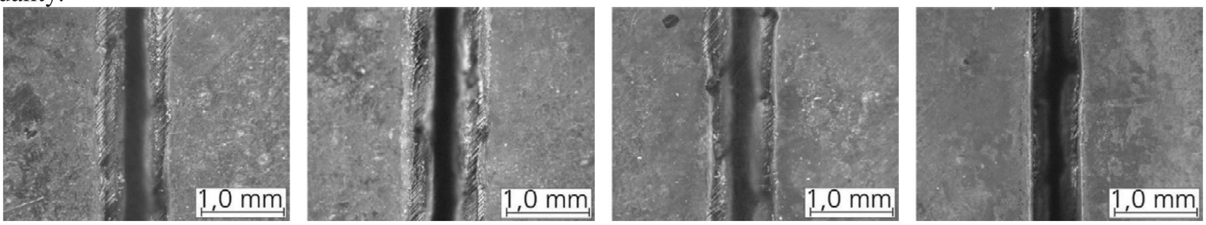
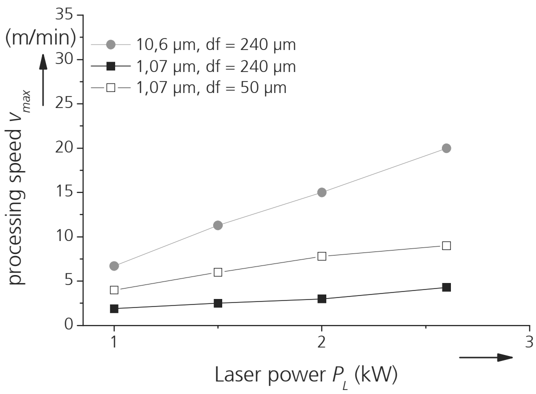


Figure 5: Top view of the cutting zone of consolidated CFRP for different laser spot velocities (0.5, 1, 2, 3 m/s, remote cut, CO_2-laser)

The results presented above were realized with a comparable laser spot diameter. The use of high brilliant laser sources like fiber lasers enables us to process with smaller focus diameters using comparable optical configurations. This means, the intensity at the laser spot can be drastically increased. The results of some remote processing trials with higher intensities are shown in Figure 6. It can be seen that the maximum processing speed is higher, but the benefit is not as high as expected. The reasons are to be found in a thinner cutting kerf and for this an increase of the aspect ratio between material thickness and kerf width. Furthermore, the interaction between evaporated material and laser beam influences the limitations in cutting speed.



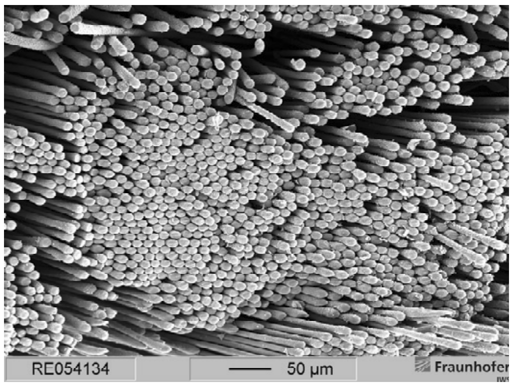


Figure 6 (left): dependence on laser power to processing speed for cutting of CFRP (process trials: remote cutting, CO_2-/ Multimode YAG laser, Singlemode – YAG – laser)

Figure 7 (right): REM – image of a carbon fiber non-crimp fabric, processed by CO_2 – remote cutting with 50 m/min

During processing (conventional or remote cutting) it is required that the evaporated material has to be taken away from the cutting zone effectively. Otherwise the heat input into the material increases and the process efficiency goes down.

As a result of the lower thickness, the carbon fiber non-crimp fabric can be cut by much higher velocities. Moreover, the absence of vinyl ester resin benefits the absorption behavior of the material regarding to fiber-laser radiation. Also, the remote-cutting edge is homogeneous (Figure7), while the gas assisted one posses irregular fringe. However, CO_2-remote-laser-processing realizes the maximum cutting velocity of more than 50 m/min for carbon fiber non-crimp fabric and multi-kW laser power.

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